A New Pulsar in Green Bank Telescope Searches of Ten Globular Clusters

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ABSTRACT

We report the results of pulsar searches in ten globular clusters using the Robert C. Byrd Green Bank Telescope. One new binary millisecond pulsar has been discovered in NGC 5986 with $P_{\rm spin} = 2.6$ ms, $P_{\rm orb} = 1.3$ d, and a minimum companion mass of 0.16 $M_\odot$. The companion is most likely a Helium white dwarf. Eight of the globular clusters we searched have central densities $< 10^4$ $L_\odot\,{\rm pc}^{-3}$, making this a good sample for studying the pulsar content of low density clusters. We find no evidence for pulsars in clusters with very low densities ($< 10^3$ $L_\odot\,{\rm pc}^{-3}$), consistent with theoretical predictions. Null results in many of clusters we searched with moderate densities indicate that these systems do not contain a bright MSP. Two clusters in particular, one with very low metallicity, stand in contrast to theoretical calculations by Ivanova et al. (2008). We also find that three body exchange interaction rates calculated by (Phinney 1996) seem to over predict the pulsar content in the clusters we studied.

Subject headings: pulsars: individual (J1546−3747A)—pulsars: general—globular clusters: individual (M92, NGC 288, NGC 2298, NGC 5897, NGC 5986, NGC 6981, NGC 7089, Pal 6, Pal 12, Terzan 9)—globular clusters: general

1.   Introduction

Over the past 23 years, 143 pulsars have been discovered in 27 globular clusters (GCs), the vast majority of which are true millisecond pulsars (MSPs) with $P_s \lesssim 10$ ms[1]. Many of these MSPs are in exotic binary systems (e.g. D'Amico et al. 2001; Ransom et al. 2005; Hessels et al. 2006; Freire et al. 2007, 2008). This stands in stark contrast to the population of pulsars found in the Galactic disk, which are dominated by isolated pulsars with longer spin periods and a small number of binary MSPs. These differences have been attributed to the high stellar densities in GC cores, where exchange interactions form mass-transferring binaries leading to the recycling of a "dead" pulsar. These exchange interactions are also responsible for the exotic binaries described above (see Camilo & Rasio 2005; Ransom 2008, for reviews). The large number of exchange interactions in GCs can in turn be traced to the high stellar densities in cluster cores, and indeed, correlations between density and the number of neutron stars in GCs have been known for some time. Pooley et al. (2003) demonstrated that the core interaction rate, $\Gamma_c \propto \rho_c^{1.5} r_c^2$, is a good predictor of the number of low-mass X-ray binaries, which are thought to be the progenitor systems to many MSPs. The value of Γ_c/D^2, where D is the distance and accounts for flux losses, has been used to pick out the most promising clusters for pulsar searches with great success. Terzan 5 (Ransom et al. 2005; Hessels et al. 2006) and 47 Tucanae (Camilo et al. 2000; Freire et al. 2003) are the two richest clusters for MSPs and have the highest value of Γ_c/D^2. Recent simulations also show a strong dependence on core density for the number of observable pulsars (Ivanova et al. 2008).

Nonetheless, there are exceptions to this rule that have been known for some time. Kulkarni et al. (1991) discovered two pulsars in the low density GCs M13 and M53. Subsequent searches uncovered a substantial population of MSPs in GCs with $\rho_c \sim 10^3$–10^4 $L_\odot$ pc^{-3}. The totals now stand at five MSPs in M5 (Wolszczan et al. 1989; Hessels et al. 2007), five in M13 (Kulkarni et al. 1991; Anderson 1993; Hessels et al. 2007), four in M3 (Hessels et al. 2007), two in NGC 6749 (Hessels et al. 2007), one in M53 (Kulkarni et al. 1991), and one in M71 (Hessels et al. 2007). These MSPs account for about 13% of all known GC pulsars, despite the clusters contributing only 3% to the total Γ_c of all GCs with pulsars. However, most of these pulsars were discovered by Hessels et al. (2007) using Arecibo, and without the exquisite sensitivity of this telescope, only a handful of pulsars would have been found. Shortly after Kulkarni et al. (1991) announced their results, Johnston et al. (1992) argued that pulsar formation in low density systems was enhanced relative to high density systems, finding $N_{psr} \propto \rho_c^{0.5}$ (though this came prior to many fruitful searches in higher

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[1]See http://www.naic.edu/~pfreire/GCpsr.html for an up-to-date list

density clusters). Sigurdsson & Phinney (1995) suggested that three-body encounters with primordial binaries could give rise to a small population of pulsars even in low-density GCs.

We have searched ten clusters using the Robert C. Byrd Green Bank Telescope (GBT). We selected GCs that had not been searched using the GBT, focusing primarily on clusters that had low central densities and large Galactic latitudes (to avoid oversubscribed LST ranges). Five clusters (NGC 288, NGC 2298, NGC 6981, NGC 7089, and Pal 12) were searched using the Parkes radio telescope (Possenti et al. 2005), but we ensured that our searches were at least twice as sensitive. Since eight of the clusters have $\rho_c < 10^4 \ \mathrm{L}_\odot \, \mathrm{pc}^{-3}$, this a good sample of deeply searched low density systems. We have discovered one new binary MSP in NGC 5986, and we discuss the implications of non-detections in the other clusters.

2. Survey Details

All our searches were carried out using the GBT and the Green Bank Ultimate Pulsar Processor (GUPPI) back-end (DuPlain et al. 2008). Observations were made at a central frequency of 2 GHz, with 800 MHz of bandwidth broken into 2048 frequency channels, although persistent radio frequency interference (RFI) reduces the usable bandwidth to 600 MHz. We used sampling times of 40.96–64 μs. Total system temperatures were typically 24–28 K. The contribution from the Galactic background was estimated by scaling the values from Haslam et al. (1982) to 2 GHz assuming a spectral index of -2.6, though this was usually $\lesssim 1$ K except for clusters at very low Galactic latitudes. The limiting flux density of each search was taken to be

$$S_{\nu,\mathrm{min}} = \frac{\beta \xi \, T_{\mathrm{tot}}}{G \sqrt{n_{\mathrm{pol}} \Delta\nu \, t_{\mathrm{int}}}} \sqrt{\frac{W}{W - P}} \tag{1}$$

where $\beta = 1.3$ accounts for digitization losses and $\xi = 10$ is our limiting S/N. T_{tot} is the total sky and system temperature, $G = 1.9$ is the telescope gain, $n_{\mathrm{pol}} = 2$ is the number of summed polarizations, $\Delta\nu$ is the usable bandwidth, and t_{int} is the integration time. P is the pulse period and W is the observed pulse width, which is a combination of the intrinsic pulse width, instrumental time resolution, and broadening of the pulse due to dispersive smearing and scattering. This calculation does not take into account sensitivity losses due to RFI or Doppler smearing of the pulse due to binary acceleration. However, we observed very little RFI in our data, and since we performed acceleration searches (see below), only pulsars in very tight binaries should have dropped below our detection threshold. Integration times and approximate limiting flux densities can be found in Table 1, along with some other properties of each cluster.

To test the accuracy of our limiting flux density estimates, we calculated the integration time necessary to just detect the lone pulsar we discovered in NGC 5986, and then blindly searched this portion of our original data. The pulsar was indeed detected with with an appropriate S/N. We are therefore confident that our reported limits are accurate.

Data were reduced using the PRESTO[2] software suite (Ransom et al. 2002). After removing RFI, de-dispersed time series were created, starting with a minimum dispersion measure (DM) of 10 $pc\,cm^{-3}$ and increasing in steps of 0.1 $pc\,cm^{-3}$ to twice the DM predicted by the NE2001 model (Cordes & Lazio 2002). Acceleration techniques were used to search for periodic signals from isolated and binary MSPs and single pulse searches were used to look for bright transient emission. To search for highly accelerated pulsars, we performed acceleration searches on $\sim$ 10–20 minute subsets of each observation. We searched up to a maximum acceleration of 800 Fourier bins in all acceleration searches. Candidate pulsars were visually inspected and grouped into likely pulsars or random noise and RFI. We were able to observe some clusters twice, which allowed us to confirm or reject candidate pulsars quickly.

3. The Binary Pulsar in NGC 5986

We discovered one new pulsar in NGC 5986, J1546−3747A, hereafter NGC 5986A (Figure 1). The pulsar was discovered in our acceleration searches with an acceleration of −26 Fourier bins, or -1.1 $m\,s^{-2}$, indicating that it is in a binary system. We conducted three follow-up observations to determine the orbit of NGC 5986A and to search for more pulsars using GUPPI in a coherent de-dispersion mode at 820 MHz, 1.5 GHz, and 2 GHz. The pulsar was detected in all three follow-up observations. We searched the 820 MHz and 2 GHz observations, but found no new pulsars. The 1.5 GHz observations were heavily contaminated with RFI, making a blind search impractical.

While these observations are not sufficient to obtain a full timing solution for NGC 5986A, they have allowed us to accurately determine the orbital parameters (see Table 2 and Fig. 2). The orbit is circular, with a period of $\sim$ 1.3 days and projected semi-major axis of $\sim$ 0.6 $R_\odot$. The companion mass limit is 0.16 $M_\odot$ assuming a pulsar mass of 1.4 $M_\odot$. Given a distribution of orbital inclinations that is flat in $\cos i$, an edge-on orbit is statistically most likely, so the true companion mass is probably close to this limit. These binary characteristics are similar to those of MSPs with Helium white dwarf companions that are found in both GCs and the Galactic disk. A main-sequence companion seems unlikely, as such systems

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[2]http://www.cv.nrao.edu/~sransom/presto/

have only been found in dense GCs (Edmonds et al. 2002; Possenti et al. 2003; Hessels et al. 2006). Furthermore, we see no evidence for eclipses, although we lack coverage near conjunction when eclipses would be most likely. Systems similar to NGC 5986A have been found in other GCs of comparable density[3]. If a precise position can be measured through future pulsar timing, a search for an optical counterpart may be feasible.

Rough flux density estimates were obtained by assuming that the off-pulse RMS noise levels are described by the radiometer equation,

$$\sigma = \frac{T_{\mathrm{tot}}}{G\sqrt{n_{\mathrm{pol}}\Delta\nu\, t_{\mathrm{int}}}}. \tag{2}$$

We find $S_\nu = 21$, 27, and 45 μJy at 2 GHz, 1.5 GHz, and 820 MHz, respectively, which yields a spectral index of $\alpha \sim -0.9$, flatter than the canonical value of -1.7.

4. The Pulsar Content of Low-Density Clusters

We searched ten clusters for pulsars, five of which have $10^3 < \rho_{\mathrm{c}} < 4 \times 10^4$ $\mathrm{L}_\odot\,\mathrm{pc}^{-3}$, but found only one MSP. This stands in contrast to previous surveys (Hessels et al. 2007, and references therein, hereafter HRS07) that found several pulsars in low density clusters. We therefore consider what factors may have led to our null results.

Fig. 3 shows the approximate limiting luminosity of our searches, where $L_{\mathrm{min}} = S_{\mathrm{min}}D^2$, along with the 1.4 GHz pseudo-luminosities of pulsars with reliable flux density measurements from HRS07, scaled to 2 GHz using a spectral index of -1.7 (NGC 5986A is also shown). It is immediately obvious that HRS07 were more sensitive than our searches. We can attribute this to two factors. The first is that all the GCs from HRS07 had $D < 8$ kpc, with the exception of M53 ($D = 17.8$ kpc). By comparison, only two clusters in our survey have $D < 8$ kpc, while most have $D > 10$ kpc. The second factor is that HRS07 were able to reach lower limiting flux densities using Arecibo than we could with the GBT.

Despite these factors, 3/10 of our searches should have been sensitive to the brightest $\sim 53\%$ of a population similar to the HRS07 pulsars, and 8/10 of our searches should have been sensitive to the brightest two pulsars. Furthermore, four out of five of the clusters with $\rho_{\mathrm{c}} > 10^3$ $\mathrm{L}_\odot\,\mathrm{pc}^{-3}$ were among the five most sensitively searched GCs in our sample. In other words, we achieved good sensitivity in the most promising clusters. As discussed in §2, we are confident that our limiting flux densities are accurate unless there are pulsars in

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[3]http://www.naic.edu/~pfreire/GCpsr.html

extremely tight binaries. However, since HRS07 used the same search procedure as we have, they suffered from the same bias, so we do not believe this is a good explanation for the lack of pulsars in our sample. While it is possible that some of the HRS07 pulsars could have a steeper spectral index than the assumed value of -1.7, we would also expect some to have flatter spectra, making them easier to detect at 2 GHz. It therefore seems likely that most of the clusters we searched lack a bright MSP.

We now turn to the theoretical results of Ivanova et al. (2008), who predict the number of neutron stars in different types of GCs through Monte Carlo simulations. They simulated a variety of clusters, including those with $\log(\rho_c/\mathrm{pc}^{-3}) = 3, 4, 5, 6$. We began by empirically fitting a simple exponential to the results of Ivanova et al. (2008) of the form

$$n_{\mathrm{psrs}} = a\, e^{\log \rho_c} + b \tag{3}$$

with $a = 0.041$ and $b = -0.82$, and where n_{psrs} is the number of pulsars formed per $2 \times 10^5\,\mathrm{M}_\odot$ (as per the Ivanova et al. (2008) simulations). We explored other functional forms but chose this one for its goodness of fit and simplicity. We then calculated the expected number of pulsars in our clusters based upon their central densities and masses[4]. Next, we calculated how many pulsars would lie above our limiting flux densities (at 2 ms), given a power-law distribution, $dN(L) \propto L^{-1}\,dL$. We assumed a maximum luminosity equal to the brightest cluster pulsars, (about $250\,\mathrm{mJy\,kpc}^2$ at 2 GHz) and a minimum luminosity of $0.16\,\mathrm{mJy\,kpc}^2$ (obtained by scaling the typically assumed lower limit of $0.3\,\mathrm{mJy\,kpc}^2$ at 1.4 GHz to 2 GHz). We calculated upper and lower estimates in the same way, fitting to the maximum and minimum expected pulsars as defined by the errors quoted in Ivanova et al. (2008).

Based on these calculations, we expect that about nine pulsars should have been detected in our sample, with upper and lower estimates of 16 and three pulsars, respectively. Our results are not very sensitive to our choices of L_{max} and L_{min} since our limiting luminosities are above the L_{min} cutoff. Choosing a flatter slope for the luminosity distribution only increases the number of potentially observable pulsars. As a check on our method, we performed the same analysis using all the clusters searched by HRS07. M15 (a dense, massive cluster with eight known pulsars) was an outlier in these calculations, with far more pulsars predicted than are observed; when it is excluded from the analysis, we predict 6^{+15}_{-6} observable pulsars in the HRS07 sample. Twenty have been discovered (excluding the eight in M15), which is consistent with this upper limit.

Phinney (1996) also gave birth rates for pulsars in GCs for different formation mechanisms, the most relevant in our density regime being three-body exchanges. The birth rates

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[4]Masses were taken from photometric models by O. Y. Gnedin; http://www.astro.lsa.umich.edu/~ognedin/gc/vesc.dat

are given per neutron star, so we once again use the results of Ivanova et al. (2008) for an estimate of the total neutron star content of our clusters. We also assume an MSP lifetime of ~ 10 Gyr. Based on these theoretical models, we should have been sensitive to ~ 1–2 pulsars each in NGC2298, Terzan 9, and NGC6981, about ten in Pal 6, about two dozen in NGC5986, ~ 50 in M92, and ~ 70 in NGC7089.

5.   Discussion

We predict that 9^{+7}_{-3} pulsars should have been observable in our sample based on the results of Ivanova et al. (2008). This prediction seems high given our single detection in NGC 5986 (we note that this cluster was predicted to contain one observable pulsar based on the high estimates of Ivanova et al. (2008)). In addition, nearly all of the potentially observable MSPs come from M92 and NGC 7089. This assertion is supported by the fact that these two clusters have the highest value of Γ_c/D^2 in our sample. As can be seen from Fig. 3, M92 in particular was searched fairly deeply, so this null result is particularly interesting. One parameter that was not taken into account in our simulations was metallicity. Surveys of Galactic and extra-galactic GCs have found ~ 3 times more bright LMXBs in metal-rich clusters (defined by [Fe/H] < -1) (Sivakoff et al. 2007; Jordán et al. 2004; Minniti et al. 2004; Kundu et al. 2002; Bellazzini et al. 1995) and it is reasonable to believe that this effect may also manifest itself in the MSP population. We note that eight of the clusters we studied have [Fe/H] < -1, and that M92 in particular has the second lowest metallicity of any Milky Way GC—the most metal poor is M15, which was greatly under-populated in MSPs based on the calculations discussed in §4. While a full treatment of metallicity effects is beyond the scope of this paper, our results may suggest that MSPs are less likely to be found in low metallicity clusters.

We find that the results of Phinney (1996) drastically over-predict the number of MSPs that should be observable in our study. One possible explanation for this discrepancy is that our assumed MSP lifetime of 10 Gyr is too long. An order of magnitude decrease in the lifetime would yield numbers that are closer to our observed results. However, based on observed spin down rates, MSPs should be very long lived. The other parameters in our calculations were the number of primordial neutron stars (which we based off of Ivanova et al. (2008)) and the rate of MSP formation through exchange encounters calculated by Phinney (1996). It therefore seems that one or both of these inputs is too large for clusters of low to moderate density. Phinney (1996) over predicts the number of observable MSPs in higher density clusters as well, so it seems that these rates may not be applicable when trying to predict the number of MSPs in a given cluster.

We thus draw the following conclusions. GC pulsar searches are still sensitivity limited, and this necessarily makes any statements about the total population of cluster pulsars a matter of extrapolation. Nevertheless, our results show no evidence for a population of pulsars in very low density systems ($< 10^3$ $L_\odot\,pc^{-3}$), which is consistent with theoretical predictions (Ivanova et al. 2008). Even given our sensitivity limits, though, it appears that clusters with densities 10^3–10^4 $L_\odot\,pc^{-3}$ are not as efficient at forming MSPs as the results of HRS07 imply. A full treatment of the effects of metallicity may shed more light on this discrepancy. We find evidence that low (and high) density GCs are either not as efficient at forming neutron stars or recycling them into MSPs through exchange interactions as earlier calculations by Phinney (1996) imply.

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Table 1.   Globular Clusters Included in Survey

ID	ℓ (deg)	b (deg)	D (kpc)	Predicted DM (pc cm^{-3})	$r_{\rm c}$ (arcmin)	$\log \rho_{\rm c}$ (L$_\odot$ pc^{-3})	$\Gamma_{\rm c}/D^2$ (%[a])	[Fe/H]	$t_{\rm obs}$ (hr)	Approximate $S_{\nu,{\rm min}}$ (μJy)
NGC 288	152.30	-89.38	8.9	28	1.35	1.78	0.03	-1.32	0.95	11
NGC 2298	245.63	-16.00	10.8	85	0.31	2.90	0.08	-1.92	3.1	6
NGC 5897	342.95	$+30.29$	12.5	61	1.40	1.53	0.01	-1.90	1.3	10
NGC 5986	337.02	$+13.27$	10.4	92.2	0.47	3.41	1.1	-1.59	2.2	7
M92	68.34	$+34.86$	8.3	43	0.26	4.30	7.0	-2.31	1.4	9
Pal 6	2.10	1.78	5.8	397	0.66	3.46	2.5	-0.91	1.2	15
Terzan 9	3.61	-1.99	7.1	422	0.03	4.42	0.14	-1.05	2.5	10
NGC 6981	35.16	-32.68	17.0	55	0.46	2.38	0.03	-1.42	1.0	11
NGC 7089	53.37	-35.77	11.5	46	0.32	4.00	3.8	-1.65	1.0	11
Pal 12	30.51	-47.68	19.0	40	0.02	3.64	0.004	-0.85	1.0	11
47 Tucanae[b]	305.89	-44.89	4.5	24.4	0.36	4.88	100	-0.72	$\cdots$	$\cdots$

[a]Normalized to 47 Tucanae.

[b]47 Tucanae has been included so that the properties of our sample can be compared to a rich GC.

Note. — Cluster parameters are taken from the 2010 version of the Harris catalog (`http://physwww.physics.mcmaster.ca/~harris/mwgc.dat`). DM estimates for all clusters except NGC 5986 and 47 Tucanae are from the NE2001 model (Cordes & Lazio 2002).

Table 2.   Timing Derived Parameters of NGC 5986

Parameter	Value
P (ms)	2.6056722466(1)
Reference Epoch (MJD)	51900
DM (pc cm^{-3})	92.17(4)
$P_{\rm b}$ (d)	1.3467116(2)
$a \sin i / c$ (s)	1.38325(4)
T_0 (MJD)	55355.67467(2)
e	$< 8 \times 10^{-6}$
ω (deg)	$\cdots$
Mass Function (M$_\odot$)	0.0016
$M_{\rm c,min}$[a] (M$_\odot$)	0.16
$N_{\rm TOAs}$	79

[a]Assuming $M_{\rm psr} = 1.4$ M$_\odot$

Note. — All parameters assume that the pulsar is at the cluster center, $\alpha = $ 15:46:03.44, $\delta = -37$:47:10.1 (Shawl & White 1986). The eccentricity limit was calculated according to $e_{\rm lim} = \delta t \, (a \sin i / c)^{-1}$ where δt is our timing precision (Phinney 1992). The orbital solution was obtained using the DE405 Solar System ephemeris and the UTC(NIST) time standard.
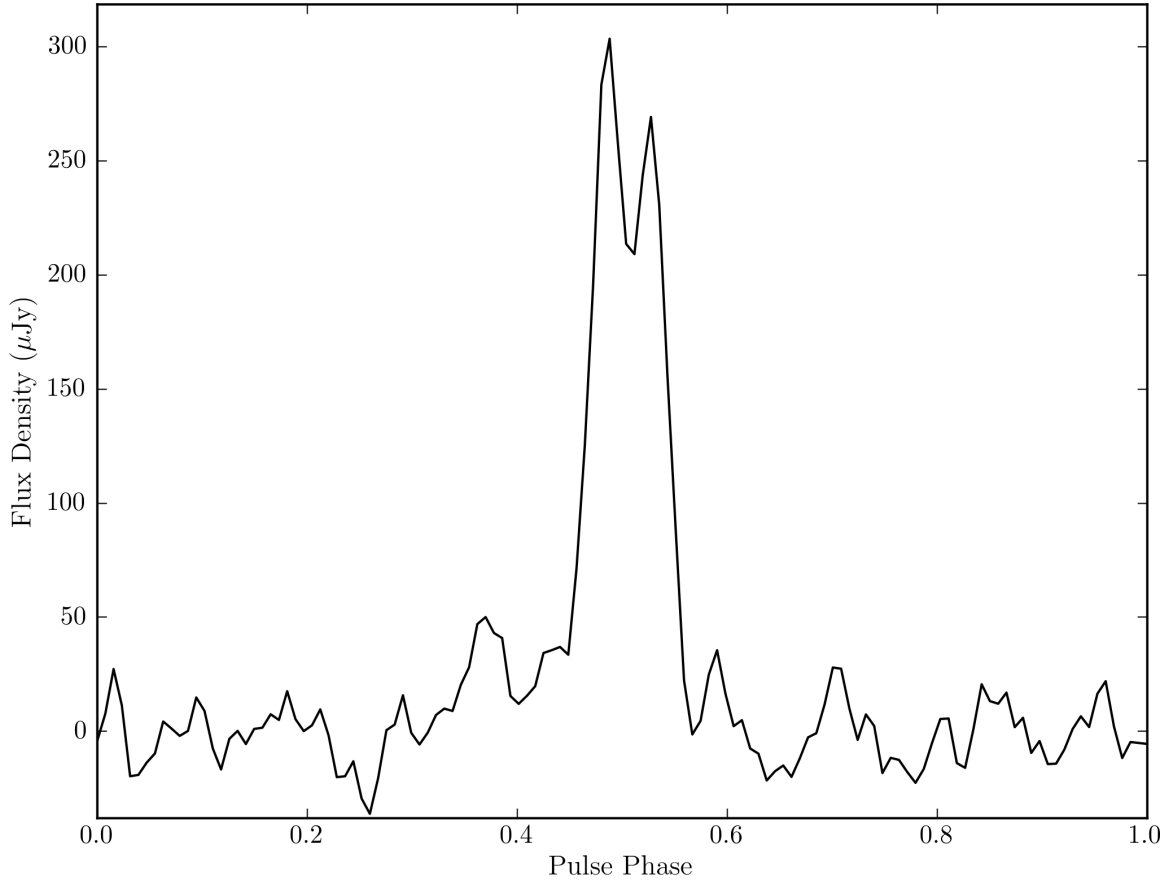
Fig. 1.— The flux-calibrated pulse profile of NGC 5986A at an observing frequency of 2 GHz $(S_\nu = 21 \ \mu\text{Jy})$.
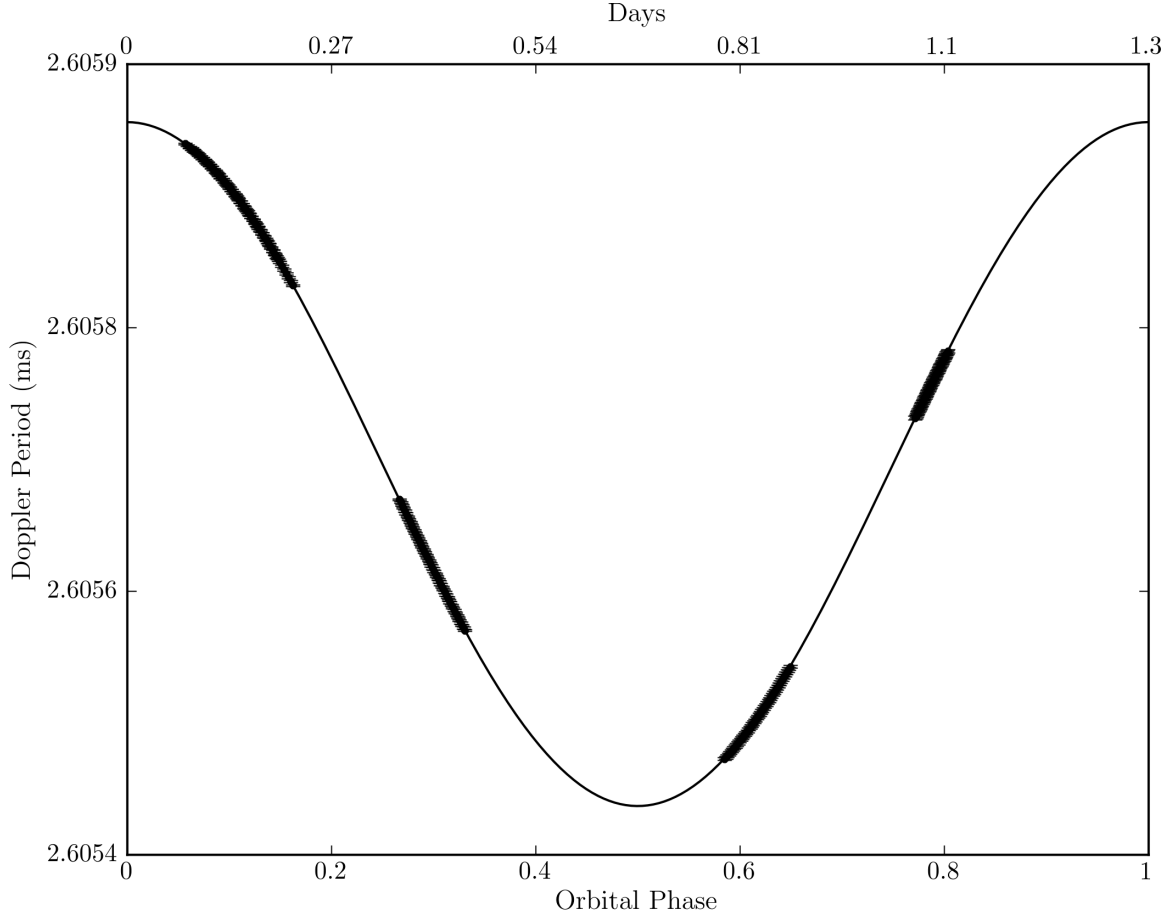
Fig. 2.— The Doppler modulated period of NGC 5986A, clearly showing the effects of binary acceleration and a circular orbit. The thick lines show the observed period during our observations, and the thin line is the predicted period based on our orbital solution.
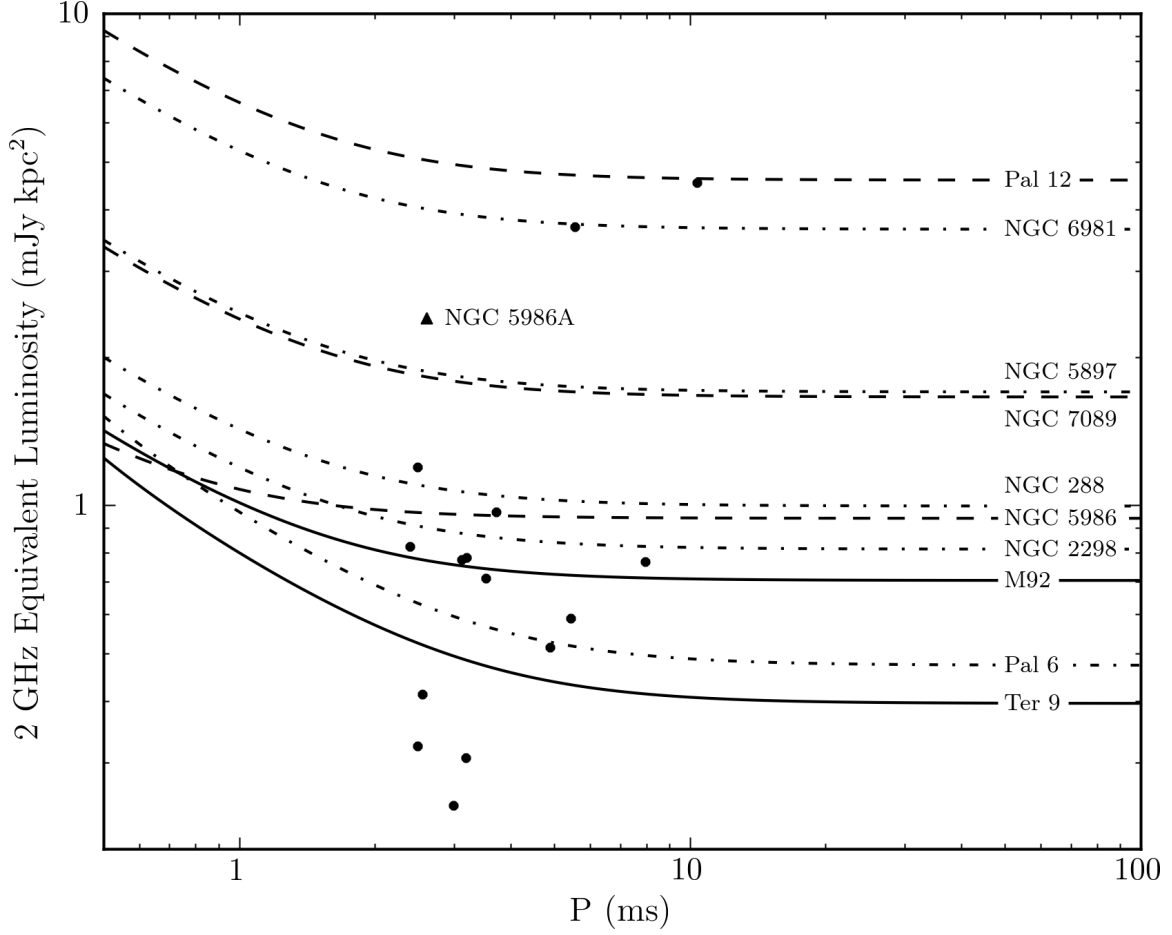
Fig. 3.— Comparison of the limiting luminosity of our searches and the luminosities of pulsars with reliable flux densities from Hessels et al. (2007), as well as NGC 5986A. Luminosities of the known MSPs were scaled from 1.4 GHz to 2 GHz using a spectral index of -1.7. Solid lines indicate clusters with $\rho_c > 10^4$ $L_\odot\, pc^{-3}$, dashed lines indicate 10^3–10^4 $L_\odot\, pc^{-3}$, and dot-dashed lines indicate $< 10^3$ $L_\odot\, pc^{-3}$.